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# Low-latitude gamma-ray sources and the hypothesis of a black hole population

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**Abstract.** We present a study of 40 unidentified 3EG gamma-ray sources which were found to be not positionally coincident with any known class of galactic objects in a previous paper (Romero, Benaglia & Torres, 1999). We have performed a variability analysis which reveals that most of these 40 sources are variable. These sources have, in addition, a steep mean value of the gamma-ray spectral index,  $\langle \Gamma \rangle = 2.41 \pm 0.2$ , which, combined with the high level of variability rules out a pulsar origin. The positional coincidences with uncatalogued candidates to supernova remnants were also studied. Only 7 sources in the sample are spatially coincident with these candidates, a result that is shown to be consistent with the expected level of pure chance association. A complementary search for weak radio counterparts was also conducted and the results are presented as an extensive table containing all significant point-like radio sources within the 40 EGRET fields. We argue that in order to produce the high variability, steep gamma-ray spectra, and absence of strong radio counterparts observed in the gamma-ray sources of our sample a new class of objects should be postulated, and that the only known candidate capable to generate such features are isolated magnetized black holes.

**Key words:** gamma-rays: observations – gamma-rays: theory – ISM: supernova remnants – black holes physics

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## 1. Introduction

The main results of the very successful Energetic Gamma Ray Telescope (EGRET) of the Compton Gamma Ray Observatory (CGRO) are contained in the Third EGRET (3EG) catalog (Hartman et al. 1999), which includes observations between 22 April 1991 and 3 October 1995, and lists 271 point sources. Of these sources, 170 have no conclusive counterparts at lower frequencies. In the latitude range  $|b| \leq 10^\circ$ , there are 81 unidentified sources, a number which doubles what was reported in the previous 2EG catalog and its supplement (Thompson et al. 1995, 1996), and clearly confirms the existence of a population of gamma-ray emitters in the Galaxy.

The nature of this population of low-latitude gamma-ray sources is not clear. Several types of objects have been proposed as possible counterparts in the past: supernova remnants (e.g. Sturmer & Dermer 1995, Esposito et al. 1996, Combi et al. 1998a), massive stars with strong winds (e.g. Montmerle 1979, Romero et al. 1999), young pulsars (e.g. Yadigaroglu & Romani 1997), and compact clouds in star-forming regions (e.g. Cassé & Paul 1980). Gehrels et al. (2000) have recently shown that there is a population of sources associated with the Gould belt, as it was originally suggested by Grenier (1995). This suggests that young stellar objects play an important role in the generation of the observed emission. In a recent paper (Romero, Benaglia & Torres 1999, hereafter Paper I), some of us presented a study of the level of positional correlation between gamma-ray sources in the 3EG catalog and a variety of galactic objects. A statistically very significant correlation was found in the case of SNRs and OB star associations. In that work it was also found that a group of 42 low-latitude 3EG sources do not present a counterpart at all. Two of these sources were finally discovered to be artifacts related with the high intensity of the Vela pulsar (Hartman 2000). Very recently, Zhang et al. (2000) proposed that most of the sources spatially coincident with SNRs and OB associations could be pulsars. They have presented a variability study of the 38 3EG sources that are coincident with objects of these classes, finding that most of them are not variable.

In this work we focus our attention on the group of 40 gamma-ray sources which are not coincident with any known galactic object. Classical galactic counterparts are expected to be non-variable on timescales of a few years. In particular, gamma-ray pulsars should not experience dramatic changes in their emission properties. Consequently, we shall extend the variability analysis of Zhang et al. (2000) to the group of 40 sources mentioned above in order to check whether they form an homogeneous population with the remaining low-latitude 3EG sources from the point of view of the variability of their emission. We shall show that these sources have a quite different behaviour that characterizes a different population, and we shall explore the possibility that the parent population be non-accreting magnetized black holes.

The structure of the paper is as follows. In Section 2 we define our sample. The variability analysis is presented in Section 3. Section 4 deals with the possible positional correlation between sources in our sample and SNR candidates not included in Green’s (1998) catalog. In Section 5 we explore possible weak radio counterparts of the gamma-ray sources and present an extensive table with all significant point-like radio sources within the 40 EGRET positional error boxes that, we expect, will be very helpful for future research in this field. In Section 6 we discuss the case for isolated Kerr-Newman black holes as possible generators of the gamma-ray source population, and finally, in Section 7, we draw our conclusions. Three appendices present detailed tables with data used in our research.

## 2. Sample

From the original set of 81 (75 if we neglect the six sources thought to be artifacts produced by the Vela pulsar) unidentified sources at  $|b| \leq 10^\circ$ , an apparently large fraction of  $\sim 50\%$  (40 sources) remain without any known galactic positional counterpart. We list these sources in Table 1, where we give their 3EG name, their galactic coordinates, the error in their position –assumed to be represented by the 95% confidence contours given by the 3EG catalog–, and their gamma spectral index  $\Gamma$  (such that the photon distribution is given by  $N(E) \propto E^{-\Gamma}$ ). We also present four further columns related to the variability analysis that will be explained below. A †-symbol on the source name indicates a source which was suggested as possible AGN by Hartman et al. (1999). It is worth noticing that the mean value of the spectral index is quite steep for these sources:  $2.41 \pm 0.2$ , steeper than the steepest pulsar spectrum known (Thompson et al. 1994). The distribution of the spectral index is shown in Figure 1. Only three sources out of 40 have  $\Gamma < 2$ .

## 3. Gamma-ray variability

We shall now assess the possible long term variability (on time-scale of years) of the sources in our sample. We will adopt the following criterion. We define a mean weighted value for the EGRET flux as:

$$\langle F \rangle = \left[ \sum_{i=1}^{N_{vp}} \frac{F(i)}{\epsilon(i)^2} \right] \times \left[ \sum_{i=1}^{N_{vp}} \frac{1}{\epsilon(i)^2} \right]^{-1}. \quad (1)$$

Here,  $N_{vp}$  is the number of viewing periods for each gamma-ray source. We take into account only single viewing periods.  $F(i)$  is the observed flux in the  $i^{\text{th}}$ -period, whereas  $\epsilon(i)$  is the corresponding error in the observed flux. For those observations in which the significance ( $\sqrt{TS}$  in the EGRET catalog) is greater than  $3\sigma$ , we took the error as  $\epsilon(i) = F(i)/\sqrt{TS}$ . However, many of the observations are in fact upper bounds on the

flux, with significance below  $2\sigma$ . For these ones, we assume both  $F(i)$  and  $\epsilon(i)$  as half the value of the upper bound. We then define the fluctuation index  $\mu$  as:

$$\mu = 100 \times \sigma_{\text{sd}} \times \langle F \rangle^{-1}. \quad (2)$$

In this expression,  $\sigma_{\text{sd}}$  is the standard deviation of the flux measurements, taking into account the previous considerations.

Results for the 40 sources are given in Table 1, where we show four columns corresponding to  $\langle F \rangle$ ,  $\sigma_{\text{sd}}$ ,  $N_{\text{vp}}$  and  $\mu$ .

In order to remove as far as possible spurious variability introduced by the observing system, we computed the fluctuation index  $\mu$  for the seven confirmed gamma-ray pulsars in the 3EG catalog (see Cusumano et al. (2000) and Kaspi et al. (2000) for the latest identifications). We adopt the physical criterion that pulsars are –i.e. by definition– non-variable gamma-ray sources. Then, any non-null  $\mu$ -value for pulsars is attributed to experimental uncertainty. We then define an averaged statistical index of variability,  $I$ , as

$$I = \frac{\mu_{\text{source}}}{\langle \mu \rangle_{\text{pulsars}}} = \frac{\mu_{\text{source}}}{26.9}. \quad (3)$$

Table 2 shows the variability results for the confirmed pulsars in the 3EG catalog, whereas the last column of Table 1 shows the results of the variability index  $I$  for our sample of unidentified 3EG sources.

The adopted variability criterion is then to consider that any source for which the  $\mu$ -value is less than the upper value of  $\mu$  for pulsars ( $\mu_{\text{max}} = 40.5$ ), is a non-variable source. At least, we can assure that for this kind of sources, and with the data now at hand, it is not possible to discriminate any significant long term variation in its gamma emission. We shall also consider that sources with  $\mu$ -values between 40.5 and 65 are marginally variable or variable, and that sources with  $\mu > 65$  are highly variable. In terms of the averaged index  $I$ , this is equivalent to say that highly variables sources will be those with  $I > 2.5$ , which is  $3\sigma$  away from the statistical variability of pulsars.

We adopted this criterion, previously used in blazar variability analysis by some of us (Romero et al. 1994) and applied to 3EG sources by Zhang et al. (2000), rather than the similar one used by McLaughlin et al. (1996) and Wallace et al. (2000) in order to have a direct comparison with the spurious statistical variability shown by pulsars. Since the  $I$ -index establishes how variable is a source with respect to the pulsar population, it can be considered as indicative of how reliable we can be about the possible physical variation in the gamma emission. The combination of the results of Zhang et al. (2000) with those presented in this paper yields the variability index for all unidentified low-latitude sources in the 3EG catalog, see Appendix C.

With the explained criterion, we find that only a low 25.0% of the sources in our sample are non-variable, 42.5% are probably variable, and 32.5% are highly variable. In Figure 2 we present the histogram for the variability index  $I$  in our sample, along with a Gaussian fit which presents its peak at  $I = 2.0$  and a standard deviation equal to  $\sigma_I = 0.7$ . In order to better evaluate these results, we have also computed the variability index for the 66 confirmed AGNs in the 3EG catalog. A table with these results (with the same columns as in Table 1) is in Appendix B. Fifty-eight AGNs are variable sources. We show in Figure 3 the distribution of the variability index for AGNs. The Gaussian fit in this case peaks at  $I = 2.3$  and a standard deviation equal to  $\sigma_I = 0.8$ . Since the distribution of the unidentified sources under study is similar to that obtained for AGNs, which is a well-known variable population, we can preliminary conclude that most of our EGRET sources may actually vary on time-scales of years.

It is worth noticing that Zhang et al.'s (2000) results show that most of the sources they have studied are non-variable. Specifically, 26 out of 38 unidentified 3EG sources positionally coincident with OB regions and SNRs have an  $I$ -index compatible with 1 (the value for pulsars) within  $1\sigma$ . The very different variability indices for Zhang et al.'s and the present samples strongly suggest that these sources are part of physically different populations.

In Figure 4 we plot the correlation between the computed value of  $\mu(I)$  and the observed value of the spectral index  $\Gamma$ , for the sources in our sample. We also show in the same figure the  $\mu(I)$ - $\Gamma$  relation for AGNs. Two solid horizontal lines denote the lower and upper bound for the statistical variability of the pulsar population. An horizontal dashed line stands for the value of the variability indices above which the variability of the sources can be established with high confidence (i.e. above  $3\sigma$  level). From these plots, it appears that several different populations are present. Pulsars should be located at the lower left corner of the figure: they have a hard spectral index and are non-variable. A different group of sources, with spectral index in the range ( $\sim 2.1, \sim 2.6$ ) and being marginally variable or variable, appears towards the center of the figure. Most of the AGNs are located in this region of the plot. Finally, some sources seem to show a steepening in their spectral index with increasing values of variability. A Spearman correlation test for the variable sources yields a probability of about 8% for this being a pure chance effect. These sources could then be members of a new population of galactic objects or, perhaps, they might be AGNs seen through the disk of the Galaxy.

Since AGNs are isotropically distributed, we can determine a mean value for the number of AGNs detected by EGRET per square degree:  $N_{\text{AGN}} = 8.9 \times 10^{-4}$  AGN/degree<sup>2</sup>. Interestingly, at latitudes in the range  $-10^\circ \leq b \leq 10^\circ$ , the number of unidentified sources that are marginally variable or variable yields a number density  $N_{\text{unid}} = 4.3 \times 10^{-3}$

objects/degree<sup>2</sup>. This shows that there are five times more variable objects within the galactic plane than away from it. Then, we have to conclude that if the distribution of AGNs is isotropic, we have an excess of variable galactic sources representing a new class of population, as it was already noticed in previous studies by McLaughlin et al. (1996), by Mukherjee et al. (1997) and very recently by Wallace et al. (2000).<sup>1</sup>

Considering the sample of the 2EG catalog, Özel and Thompson (1996) argued that one half or more of the unidentified EGRET sources lying at high latitudes are of galactic origin. Nice and Sawyer (1997) found no evidence that pulsars were the constituents of this putative galactic population. This agrees with our results, since we show here that this new class of galactic objects should resemble, from the point of view of gamma-ray observations, the AGN population.

A preliminary conclusion of this section could then be stated as follows: A new population of galactic objects is needed to explain the behaviour of some unidentified 3EG sources. This population must be able to display steep gamma-ray spectral indices together with significant gamma-ray variability. Fig. 4 suggests that our sample, although mostly of galactic origin, mimics some observational properties of AGNs.

#### 4. Uncatalogued supernova remnants

We consider in this section whether some of the sources in our sample may be associated with recently proposed candidates to supernova remnants, presently not catalogued by Green (1998). Our interest in this search resides in the fact that young stellar objects like recently formed black holes and pulsars can still be associated with the gaseous remnant of the original supernova that created them.

The diffuse non-thermal emission of the galactic disk, originated in the interaction of the leptonic component of the cosmic rays with the galactic magnetic field, is surely veiling many remnants of low surface brightness. Recent observational studies using filtering techniques in the analysis of radio data have revealed several new SNR candidates that are not yet included in the latest issue of Green's catalog, which was used in the study presented in Paper I (e.g. Duncan et al. 1995, Combi & Romero 1998, Combi et al. 1998b, 1999a, Jonas 1999). In general, these new candidates are much more extended than those previously known. There are 101 of these weak non-thermal structures detected so far in the Galaxy. This number significantly extends Green's (1998) catalogue, which currently has 220 confirmed SNRs. The list of these new candidates, compiled from the papers and studies above mentioned is being published electronically as an Appendix.

With the aim of finding the positional coincidences between our sample of 40 3EG unidentified sources and the uncatalogued candidates to SNRs, we used the code de-

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<sup>1</sup> The latter work focus only on very short timescales.

veloped in Paper I. We have found that only 7 gamma-ray sources in our sample are positionally coincident with non-thermal radio structures. The positional coincidences thus obtained are shown in Table 3, where we give the name of the gamma-ray sources, the central position of the SNR candidates, the distance from the EGRET source to the centre of the radio structure ( $\delta$ ), and the addition of the radius of the extended sources and the uncertainty in the position of the EGRET detections ( $\Delta$ ).

To estimate the statistical significance of these coincidences, we have numerically simulated a large number of synthetic sets of EGRET sources using the code described in Paper I. As in that paper, the simulations were constrained to preserve the original gradient in the number distribution of unidentified gamma-ray sources towards the galactic plane. The results of this study show that the expected number of chance associations is  $10.4 \pm 2.7$ , quite compatible with the actual result. We conclude, then, that there is no statistical evidence suggesting that the 3EG sources analyzed in our sample are associated with known SNRs.

## 5. Search for extended radio counterparts in selected sources

We have especially studied the radio sky towards the best estimate positions of the unidentified 3EG sources J0241+6103, J0435+6137, J0628+1847, J1014-5705, J1631-4033, J1735-1500, J1828+0142, J1928+1733, J2035+4441 and J2206+66. From Table 1, it can be seen that these sources can be grouped into two sets, at the extremes of the variability and spectral index ranges. On one hand, we have six sources with low variability and relatively hard spectral indices. These sources could, in principle, be associated with pulsars or with unknown new SNR candidates. Only one of them, 3EG J1631-4033, presented positional superposition with a known candidate to SNR (see Table 3). There are, on the other hand, four sources with high variability ( $\mu$ -values ranging from 90 to 238.9) and steep spectral index ( $\Gamma$  ranging from 2.08 to 3.24).

We used continuum radio data at 1420 and 2400 MHz, from the surveys by Reich & Reich (1986) and Duncan et al. (1995) in order to study the possible presence of weak and extended radio sources within the EGRET positional error boxes of this set. Specifically, we searched for yet undetected low-brightness SNRs that could be associated with the pulsars or the black holes created in the original supernova explosion. We remove the background diffuse radiation using the Gaussian filtering technique described in a recent series of papers by Combi and coworkers (e.g. Combi & Romero 1995, 1998; Combi et al. 1998a, b, 1999a,b). The reader is referred to these papers for details. Three of the fields that were studied presented features interesting enough as to deserve individual description. Below we briefly comment on two of them: 3EG J0435+6137 and 3EG J1631-40. The source 3EG J1828+01 is discussed separately in the paper by Punsly et al. (2000).

The remaining fields were empty of extended radio structures or too confused even after background subtraction as to provide reliable information.

### 5.1. 3EG J0435+6137

In Figure 5, upper panel, we show the filtered radio image of the region around 3EG J0435+6137 at 1.42 GHz (with an rms noise of 20 mK and angular resolution of  $34'$ ) super-imposed to the EGRET probability contours. Two apparently extended radio sources are visible in the field. The strongest one, 87GB J0443+6118, is partially outside the 95% confidence contour of the gamma-ray detection. Another source, named 87GB J0441+6145, is located  $20'$  away from the best estimated position of 3EG J0435+6137, well within the 95% confidence contour.

In Fig. 5, lower panel, we show the central region of the radio field at 5 GHz and a resolution of  $3.5'$  (Condon et al. 1989). Several point-sources are visible in the frame. The identification of the main ones is also indicated in the figure. None of these sources is known to be extragalactic. One of them, 87GB J0442+6140, is coincident with the X-ray source 1RXS J044239.3+61404. Another source, 87GB J0435+6137 (also known as TXS 0431+615), is located exactly at the best estimated position of 3EG J0435+6137. This source has a steep spectral index of  $\sim -1.2$ .

We have made Gaussian convolutions of those groups of point sources that are nearly coincident with the apparent extended sources seen in the lower resolution map of the upper panel, using a beamwidth of  $34'$ . We have found that both apparent structures are likely artifacts resulting from the merging of the several point-like sources in the region and that, consequently, no extended nonthermal source can be associated with 3EG J0435+6137. The counterpart, if it exists at all, should be one of the point sources. The most promising candidates seems to be 87GB J0442+6140, which is also detected at X-ray, and 87GB J0435+6137, which is the strongest one at 5 GHz.

### 5.2. 3EG J1631-4033

Figure 6 shows the filtered radio continuum map of the field around 3EG J1631-4033 at 2.4 GHz (with an rms noise of  $12 \text{ mJy beam}^{-1}$  and an angular resolution of  $10.4'$ ). The confidence contours of the likelihood test statistics of the EGRET detection are also shown as a superposed gray-scale. Four point-like radio sources can be identified with PMN sources (Griffith & Wright 1993), namely (listed by increasing Galactic longitude), PMN J1627-3952 (noted as S1 in Figure 6), PMN J1631-4015 (S2), PMN J1636-4101 (S3), and PMN J1631-3956 (S4). The angular separation between the location of the highest likelihood test statistic for the gamma-ray source and the position of PMN J1631-4015 is just  $\sim 22$  arcminutes. The strongest source, located at  $(l, b) \sim (341.9^\circ, +4.15^\circ)$ , can



be identified with PMN J1636-4101. We summarize the radio information on the point sources in Table 4. Any of these sources can be considered as a potential counterpart. Additional, weaker sources in this region are listed in Table 5 (see below).

Another interesting feature revealed by the radio map is the existence of a minimum in the continuum emission towards the centre of the field at  $(l, b) \sim (341.2^\circ, +4.6^\circ)$ . This might be the relic of an old explosive event in the ISM in this region.

## 6. Point-like counterparts: systematic search

We have searched CATS (Verkhodanov et al. 1997), SIMBAD and NED databases for any possible radio counterparts for the gamma-ray sources in our sample. We have prepared a table containing the results of this search. This table (Table 5, which is published only in electronic form due to its length) lists all significant point-like radio sources, with flux densities above 30 mJy at least at one wavelength, found within the 95 % EGRET confidence contours of the 42 gamma-ray sources of Table 1.

In Table 5 there are entries for each gamma-ray source listing, from left to right, radio survey used, source name, right ascension and declination with the corresponding uncertainties, observing frequency, flux density and its error, and comments. The different fields are separated, and within each field, and listed in increasing observing frequency, a different paragraph corresponds to each radio source. All listed sources (about 600 sources, ranging from just a few to almost 50 per 3EG field) are located within the EGRET 95% confidence contours. The material contained in this table could be very useful for future research in this field.

## 7. Discussion: The black hole hypothesis

The existence of a significant number of variable gamma-ray sources with steep spectra and without strong radio or X-ray counterparts can be explained postulating a galactic population of magnetized black holes (Punsly 1998a, b, 1999). In these objects, strong magnetic fields ( $\sim 10^{11}$  G) are supported by an orbiting charged ring or disk. The black hole itself is also charged and rotating (Kerr-Newman black hole), but the entire configuration has zero net charge, in such a way that it is not quickly neutralized by the accretion of diffuse interstellar matter. The resulting object has a magnetosphere similar to that presented by pulsars. However, because of the absence of a solid surface, thermal X-rays are not produced as in a neutron star. In addition, there is no accretion disk capable of generating strong X-ray emission as it is expected in microquasars. The radiation of the system, which is non-pulsating due to the alignment of the rotation and magnetic axes, is produced by synchrotron and inverse Compton mechanism in two relativistic electron-positron jets which propagate along the rotation axis in opposite directions, as it occurs

in AGNs. Contrary to the case of most AGNs, no redshifted emission lines should be present and, in contrast to BL Lacs, no weak nebulosity is expected in the optical band. Punsly et al. (2000) have recently shown that, when pair annihilation effects are taken into account in the calculation of the spectral energy distribution presented by magnetized black holes, a steep gamma-ray spectrum is produced. Variability naturally results in the model as the effect of shocks and firehose instabilities which induce large changes in the Doppler enhancement factor of the relativistic jets (Punsly et al. 2000).

At high energies, self-Compton losses provide most of the gamma-ray luminosity, reaching values in the range  $10^{34} - 10^{35}$  erg s $^{-1}$  for black holes of a few solar masses and polar magnetic fields of  $\sim 10^{11}$  G (see Punsly et al. 2000 for details). If such an object is relatively close (e.g.  $\sim 1$  kpc), it could appear as a typical unidentified EGRET source with  $\Gamma \sim 2.5$  or steeper. Although the spectral energy distribution is broad, only weak emission at longer wavelengths is expected. Radio counterparts, for instance, would present flux densities on the order of a few to a few tens of mJy at 5 GHz.

In the magnetized black hole model, the gamma-ray sources with the steepest spectral indices are those with large annihilation excess above the inverse Compton spectrum. These are also sources with jets containing large pair number densities. In order to see this note that the annihilation luminosity is  $\propto n^2$  and the inverse Compton luminosity of an SSC jet goes as  $n^2 \gamma_{\text{th}}^4 B$ , where  $n$  is the particle (lepton) density. The annihilation luminosity is dominated by the low energy leptons, thus it depends primarily on  $n^2$ . By contrast, the inverse Compton gamma-ray luminosity depends on other factors as well, such as the thermal Lorentz factor of the leptons,  $\gamma_{\text{th}}$ , and the magnetic field strength,  $B$ . Consequently, the largest annihilation excesses above the pure inverse Compton spectrum would occur for large values of  $n$ . However, we only expect a modest correlation of  $n$  with annihilation excess since the inverse Compton luminosity scales with this parameter as well. In order to see how one could get a mild correlation between spectral index (large annihilation excess) and variability, note that such dense jets are prone to plasma instabilities. For example, in magnetized plasmas, macroscopic anisotropic-pressure-driven instabilities exist in the hot fluid equations of MHD (e.g. Stix 1992). In a pair plasma, synchrotron cooling will most likely cause radiative losses of the random transverse (thermal) energy in a magnetized jet. Alternatively stated,  $T_{\parallel} \gg T_{\perp}$ , the parallel temperature (pressure) greatly exceeds the transverse temperature (pressure). One of the instabilities resulting from the expected pressure anisotropy in a jet is associated with the shear Alfvén wave: the firehose instability. The fastest growing modes of the firehose instability have a growth rate  $\text{Im}(\omega) \propto n^{1/2}$ . Consequently, very dense jets with large annihilation luminosity (steep spectral indices) tend to be very firehose unstable and the resulting wobble varies the Doppler factor,  $\delta$ , and hence the total gamma-ray luminosity,  $L \propto \delta^p$

(where  $p = 3$  for a jet and  $p = 4$  for a spherical region). Thus, one would expect a mild correlation in variable gamma-ray sources between the variability and spectral indices, as seemingly observed in Figure 4.

Apart from 3EG J1828+0142, the source 3EG J0241+6103 (2EG J0241+6119) was already suggested as a possible identification of a magnetized black hole by one of us (Punsly 1999a,b). The source 2EG J0241+6119 is known to be variable since the work by Tavani et al. (1998), who discarded a pulsar origin. This source appeared in a search for gamma-ray emitters, with strong emission also in X-rays, but weak output in radio. The binary system LSI +61°303, which is within the 95% probability contour of the gamma-ray detection, contains an unseen compact object suggested as the possible generator of the observed gamma rays (Punsly 1999a, b). However, a positive identification with the 3EG detection is not conclusive because of the fact that there is no signature in the gamma emission that can be correlated with the binary dynamics. Note that the magnetized black hole model in Punsly (1999b) does not produce any modulation of the gamma-ray signal on orbital time scales to first order.

## 8. Conclusions

In this paper we have shown that there exists a significant population of unidentified, low-latitude, gamma-ray sources with the following characteristics:

1. They do not positionally coincide with any known galactic object such as Wolf-Rayet or Of massive stars, catalogued SNRs, and OB associations. The probability that a set of 40 sources lacks any positional correlation with these galactic objects totally by chance is less than  $3 \times 10^{-4}$ .
2. Even considering positional coincidences with 101 identified candidates to SNRs, in addition to Green's (1998) catalog, only 7 out of 40 sources present correlation, which is consistent with the mere effect of chance.
3. The sample presents strong variability: only 10 sources out of 40 are non-variable, the rest are variable on timescales ranging from months to years. This result has to be compared with the study of Zhang et al. (2000) which showed (using the same variability analysis adopted for this paper) that most of the sources positionally coincident with OB associations and SNRs in Romero et al. (1999) are non-variable (see Appendix C). The very different variability indices for Zhang et al.'s and the present samples indicate that these sources are part of physically different populations.
4. The sample presents a steep average spectral index  $\langle \Gamma \rangle = 2.41 \pm 0.2$ ; only 3 out of 40 sources have  $\Gamma < 2$ .
5. Due to isotropy constraints on the average density of active galactic nuclei, not all of the 40 sources considered here can be AGNs seen through the disk of galaxy. The

surface density of variable unidentified sources at low galactic latitudes is five times higher than that of AGNs out of the plane. This, and the fact that there are 5 AGNs already detected at  $|b| \leq 10^\circ$ , makes that if the distribution of AGNs is isotropic, just a few out of 40 gamma-ray sources could be AGNs. Indeed, if we extrapolate the AGN number density out of the plane to latitudes within  $(-10^\circ, 10^\circ)$ , we would expect 6.5 AGNs to be detected by EGRET, leaving room just for a couple of remaining unidentified objects to be AGNs.

Altogether, these features are not in accordance with usual models of gamma-ray emitters: they can not be explained by pulsars, SNRs in interaction with nearby clouds, massive stars or AGNs. In addition, we have found an apparent trend for sources with higher degree of variability to present steeper photon spectral indices. This latter result, however, needs confirmation with the more complete sample to be obtained by the next generation of gamma-ray satellites (Gehrels et al. 1999).

To our knowledge, the only model capable to reproduce all the peculiar features presented by the sources in our sample (steep spectral gamma-ray index, high variability, absence of clear lower-frequency counterparts, etc) is that of isolated Kerr-Newman black holes (Punsly et al. 2000). This does not mean that all sources in our sample should actually be black holes, but only that an important fraction of them could be formed by these exotic objects.

Invoking galactic black holes to explain the observed behavior of some objects is not new in astrophysics. However, until now the strongest candidates have been X-ray sources and soft gamma-ray emitters. Recently, for instance, black holes have been proposed as the explanation of soft gamma-ray repeaters, in the form of microquasars (Mirabel & Rodríguez 1994). In these cases, however, the black holes are always accreting from stellar companions. Charged and rotating black holes, on the contrary, are isolated, non-accreting strong gamma-ray sources.

Our hypothesis of a population of magnetized black holes in the Galaxy can be tested with the forthcoming GLAST and INTEGRAL satellites, which will allow to increase the sample and measure the spectral energy distribution for particular sources with high precision. In the case of INTEGRAL, the spectrometer SPI and the imager IBIS could detect the electron-positron annihilation features of the black hole jets as indicated by Punsly et al. (2000). We might be, consequently, on the verge of unveiling the existence of isolated stellar mass Kerr-Newman black holes in the Galaxy.

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tic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

## Appendix A: SNR candidates

In this appendix we present the complete list of 101 candidates to SNRs that were used in our study of positional coincidences. This list is presented electronically in Table 6 and it consists of three columns: galactic coordinates ( $l, b$ ) and the diameter of the extended source ( $\theta$ ) in arcminutes. The positions of these sources were reported by Duncan et al. (1995), Combi & Romero (1998), Combi et al. (1998b, 1999a), and Jonas (1999). In general, these new candidates are much more extended and weaker than those previously known.

## Appendix B: Variability of AGNs

In this appendix we present the data for the variability indices of the 66 AGNs already detected in the 3EG catalog. These data were used both in Figure 4 and for making a comparison with our sample in the main text. We provide electronically (Table 7) the same columns as those given in Table 1 for the unidentified sources.

## Appendix C: Variability analysis of all low latitude gamma-ray sources

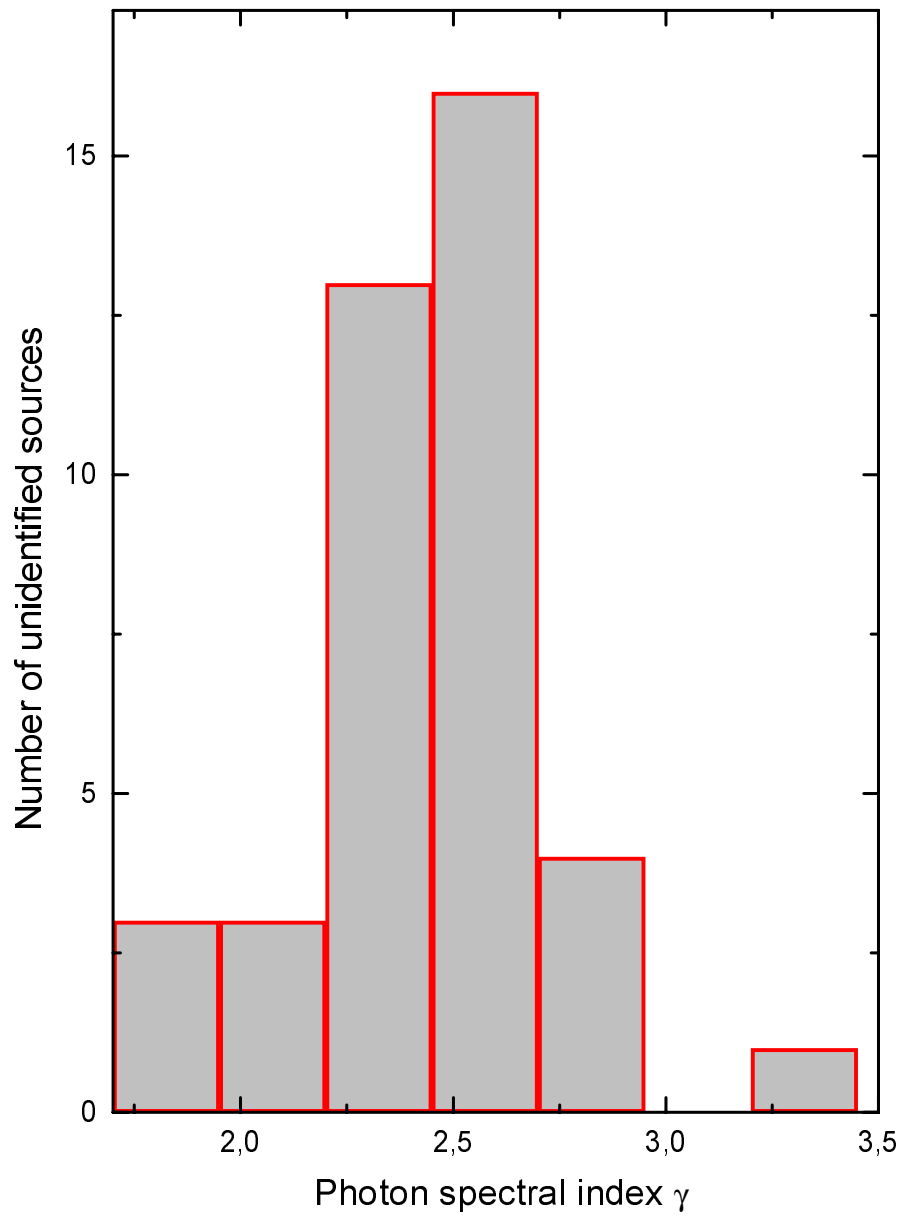
If we combine the present work with that of Zhang et al. (2000), who studied the variability of the sources which were positionally coincident with OB associations and SNRs as discovered by Romero et al. (1999), we can now make an assessment of the variability of the whole sample of unidentified sources at low galactic latitudes. There are 81 such sources, six of them (3EG J0824–4610, 0827–4247, 0828–4954, 0841–4356, 0859–4257 and 0848–4429) were recently reported to be artifacts produced by the high intensity emission of the near Vela pulsar. Another one, 3EG J0747–3412, was found to be coincident only with a WR star by Romero et al. (1999), and its variability index is here reported by the first time to be  $I = 2.81$ . For future reference we present electronically in Table 8 the 3EG source name and the variability index  $I$  for all low-latitude unidentified sources, normalized to the seven pulsars known to date.

The overall analysis of the variability of the sources is presented in Figure 7. From the total of 75 relevant detections, 45.3% are non-variable and 54.6% variable or highly variable sources. However, when the total sample is subdivided into those which do present positional correlation with SNRs, OB associations or massive stars and those which do not, a comparison of the results strongly suggest that the new set of sources analyzed in this paper can not be supported by standard models.

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**Fig. 1.** Distribution of the spectral index of the 40 unidentified sources.



**Table 1.** Unidentified 3EG sources without known possible galactic counterparts.

$\gamma$ -Source (3EG J)	$l$ (deg)	$b$ (deg)	$\Delta\theta$	$\Gamma$	$\langle F_\gamma \rangle \times 10^{-8}$ (ph cm $^{-2}$ s $^{-1}$ )	$\sigma_{\text{sd}}$	$N_{\text{vp}}$	$\mu$	$I$
0241 +6103*	135.87	0.99	0.18	$2.21 \pm 0.07$	69.4	24.6	9	35.4	1,31
0323 +5122	145.64	-4.67	0.55	$2.38 \pm 0.41$	17.5	9.5	6	54.2	2,01
0416 +3650†	162.22	-9.97	0.63	$2.59 \pm 0.32$	21.1	14.9	10	70.6	2,61
0435 +6137	146.50	9.50	0.66	$2.46 \pm 0.35$	18.8	5.1	4	27.1	1,00
0459 +3352	170.30	-5.38	0.98	$2.54 \pm 0.24$	21.9	7.6	11	34.7	1,28
0500 +2529	177.18	-10.28	0.36	$2.52 \pm 0.32$	14.2	8.4	17	59.1	2,19
0510 +5545	153.99	9.42	0.71	$2.19 \pm 0.20$	22.5	11.3	9	50.2	1,86
0520 +2556	179.65	-6.40	0.86	$2.83 \pm 0.24$	25.0	8.5	13	30.0	1,11
0521 +2147	183.08	-8.43	0.45	$2.48 \pm 0.15$	28.5	13.9	15	48.8	1,81
0533 +4751	162.61	7.95	0.60	$2.55 \pm 0.23$	18.2	6.1	8	33.5	1,24
0546 +3948	170.75	5.74	0.67	$2.85 \pm 0.21$	17.5	8.1	13	46.3	1,71
0556 +0409	202.81	-10.29	0.47	$2.45 \pm 0.16$	19.3	8.8	10	45.6	1,69
0628 +1847	193.66	3.64	0.57	$2.30 \pm 0.10$	32.9	12.0	10	36.5	1,35
0903 -3531	259.40	7.40	0.58	$2.66 \pm 0.24$	22.4	9.4	6	41.9	1,55
1014 -5705	282.80	-0.51	0.67	$2.23 \pm 0.20$	47.5	18.9	10	39.8	1,47
1316 -5244	306.85	9.93	0.50	$2.54 \pm 0.18$	19.7	11.8	11	59.8	2,21
1631 -4033	341.61	5.24	0.89	$2.25 \pm 0.27$	32.3	11.0	11	34.0	1,26
1633 -3216	348.10	10.48	0.87	$2.58 \pm 0.24$	16.1	9.5	12	59.0	2,18
1638 -5155	334.05	-3.34	0.68	$2.56 \pm 0.21$	45.3	29.9	15	66.0	2,44
1704 -4732	340.10	-3.79	0.66	$1.86 \pm 0.33$	29.5	23.6	18	80.0	2,96
1717 -2737	357.67	5.95	0.64	$2.23 \pm 0.15$	32.9	17.8	18	54.1	2,00
1735 -1500	10.73	9.22	0.77	$3.24 \pm 0.47$	19.0	45.4	19	238.9	8,86
1736 -2908	358.79	1.56	0.62	$2.18 \pm 0.12$	49.6	32.4	21	65.3	2,42
1741 -2050	6.44	5.00	0.63	$2.25 \pm 0.12$	33.4	19.1	19	57.2	2,12
1741 -2312	4.42	3.76	0.57	$2.49 \pm 0.14$	34.0	19.8	19	58.2	2,15
1744 -3934	350.81	-5.38	0.66	$2.42 \pm 0.17$	26.5	21.8	20	82.2	3,04
1746 -1001	16.34	9.64	0.76	$2.55 \pm 0.18$	29.7	25.6	18	86.2	3,19
1757 -0711	20.30	8.47	0.68	$2.51 \pm 0.20$	33.6	18.2	15	54.2	2,01
1800 -0146	25.49	10.39	0.77	$2.79 \pm 0.22$	25.5	13.3	14	52.1	1,93
1810 -1032	18.81	4.23	0.39	$2.29 \pm 0.16$	31.5	22.2	17	70.5	2,61
1812 -1316	16.70	2.39	0.39	$2.29 \pm 0.11$	43.0	30.2	18	70.3	2,60
1828 +0142	31.90	5.78	0.55	$2.76 \pm 0.39$	30.8	44.3	8	143.8	5,33
1834 -2803	5.92	-8.97	0.52	$2.62 \pm 0.20$	17.9	13.7	20	76.5	2,83
1837 -0606	25.86	0.40	0.19	$1.82 \pm 0.14$	57.5	37.4	12	65.0	2,41
1904 -1124	24.22	-8.12	0.50	$2.60 \pm 0.21$	22.5	17.7	14	78.6	2,91
1928 +1733	52.91	0.07	0.75	$2.23 \pm 0.32$	38.6	41.6	10	107.7	3,99
1958 +2909	66.23	-0.16	0.57	$1.85 \pm 0.20$	35.6	16.2	10	45.5	1,68
2035 +4441	83.17	2.50	0.54	$2.08 \pm 0.26$	39.1	35.4	14	90.5	3,35
2100 +6012†	97.76	9.16	0.48	$2.21 \pm 0.25$	23.3	8.7	7	37.3	1,38
2206 +6602†	107.23	8.34	0.88	$2.29 \pm 0.26$	25.4	4.6	4	18.1	0,67

\*: This source also displays short-term variability (Wallace et al. 2000).

**Table 2.** Statistical variability of pulsars. The first five were identified in the 3EG catalog, the last two were identified by Cusumano et al. (2000) and Kaspi et al. (2000) respectively.

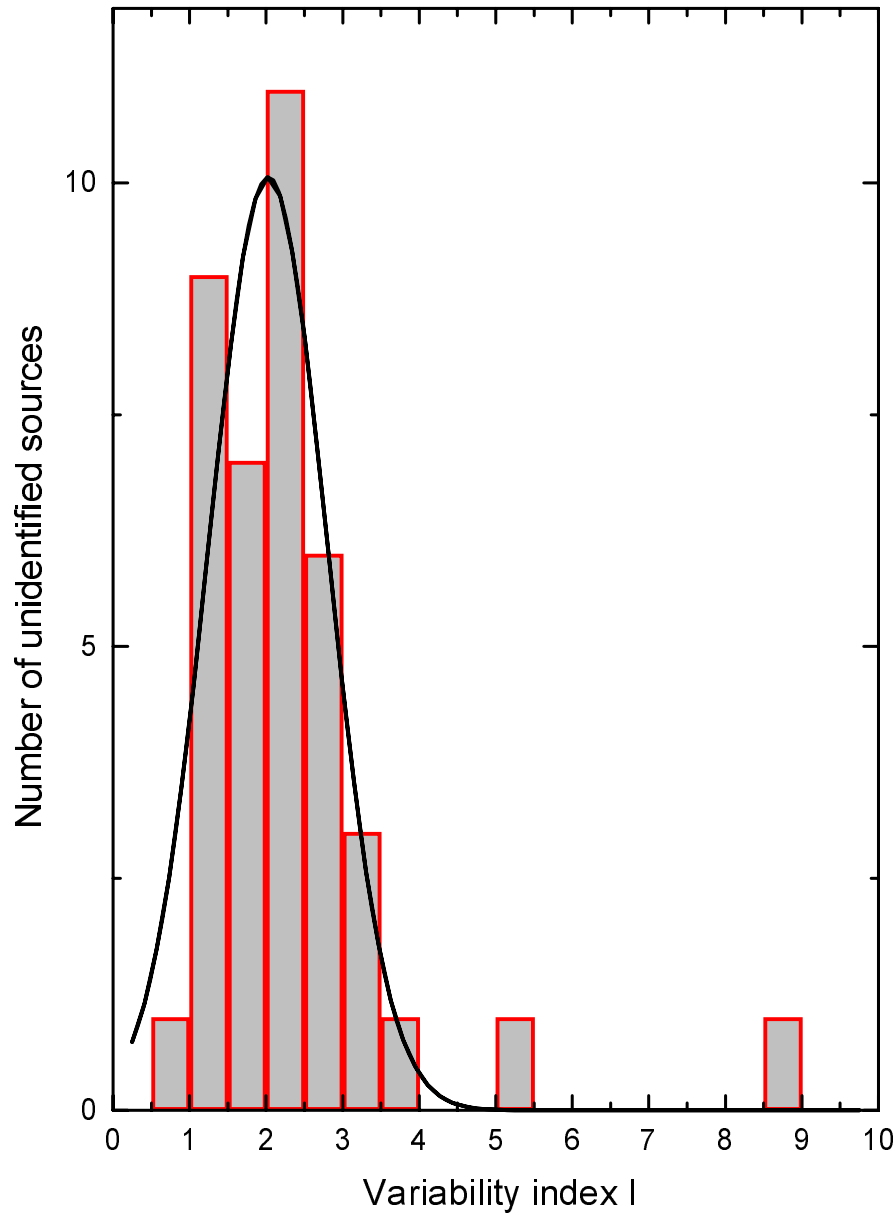
$\gamma$ -Source (3EG J)	Pulsar Name	$l$ (deg)	$b$ (deg)	$\langle\Gamma\rangle$	$\langle F_\gamma \rangle \times 10^8$ (ph cm $^{-2}$ s $^{-1}$ )	$\sigma_{\text{sd}}$	$N_{\text{vp}}$	$\mu$
0534 +2200	Crab	184.5	−5.8	2.19	219.0	29.2	16	13.3
0633 +1751	Geminga	195.0	4.3	1.66	350.9	50.1	14	14.3
0834 −4511	Vela	263.5	−2.8	1.69	848.2	183.6	8	21.6
1058 −5234	PSR B1055−52	286.1	6.5	1.94	36.1	14.6	15	40.4
1710 −4439	PSR B1706−44	343.0	−2.8	1.86	109.9	44.5	20	40.5
0634 +0521		206.1	−1.4	2.03	25.5	7.2	9	27.6
1048 −5840		287.5	0.4	1.97	61.8	18.1	13	31.0

**Table 3.** Positional coincidences with candidates to SNRs.

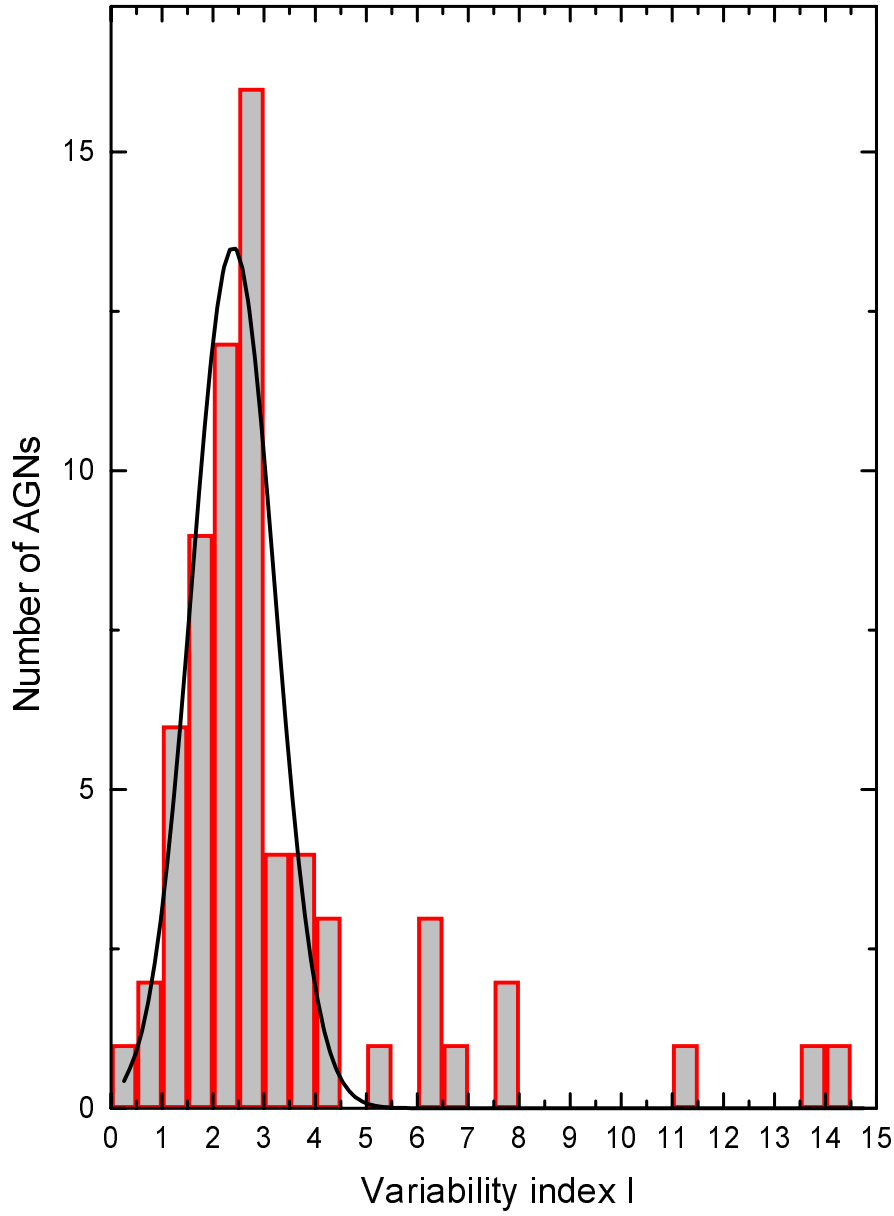
$\gamma$ -Source (3EG J)	$l$ (deg)	$b$ (deg)	$\delta$ (deg)	$\Delta$ (deg)
0903 −3531	260.20	1.40	6.05	13.58
1631 −4033	342.60	8.20	3.11	3.89
1638 −5155	333.00	0.00	3.50	3.68
1704 −4732	340.80	−4.80	1.22	2.11
1717 −2737	356.90	8.50	2.66	5.39
1834 −2803	7.30	−5.30	3.91	4.12
1837 −0606	27.00	0.50	1.14	3.69

**Table 4.** Characteristics of the point-like radio sources inside the  $\gamma$ -ray contour of 3EG J1631-4033

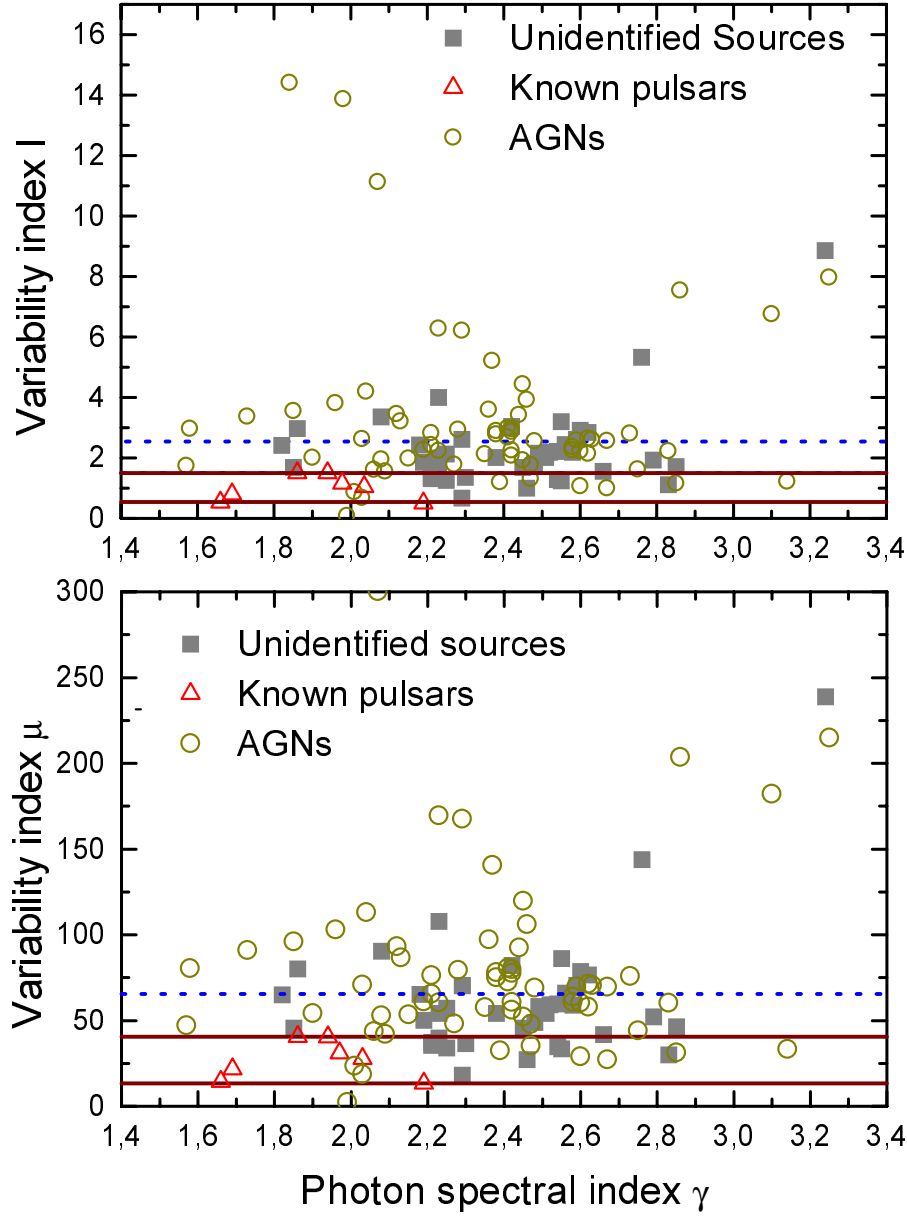
Source	$(l, b)$ (deg, deg)	$F_{2.4\text{GHz}}$ (mJy)	$F_{4.8\text{GHz}}$ (mJy)	$F_{8.3\text{GHz}}$ (mJy)	$\alpha_{2.4/4.8}$	$\alpha_{4.8/8.3}$	ID
S1	(341.6,+6.2)	877.3	670.1	−	−0.3	−	PMN J1631−4015
S2	(341.8,+5.4)	892.1	490.0	150.2	−0.8	−2.0	PMN J1627−3952
S3	(341.9,+4.1)	2260.3	1120.0	700.0	−1.0	−0.8	PMN J1636−4101
S4	(342.1,+5.6)	520.2	180.0	50.0	−1.5	−2.2	PMN J1631−3956



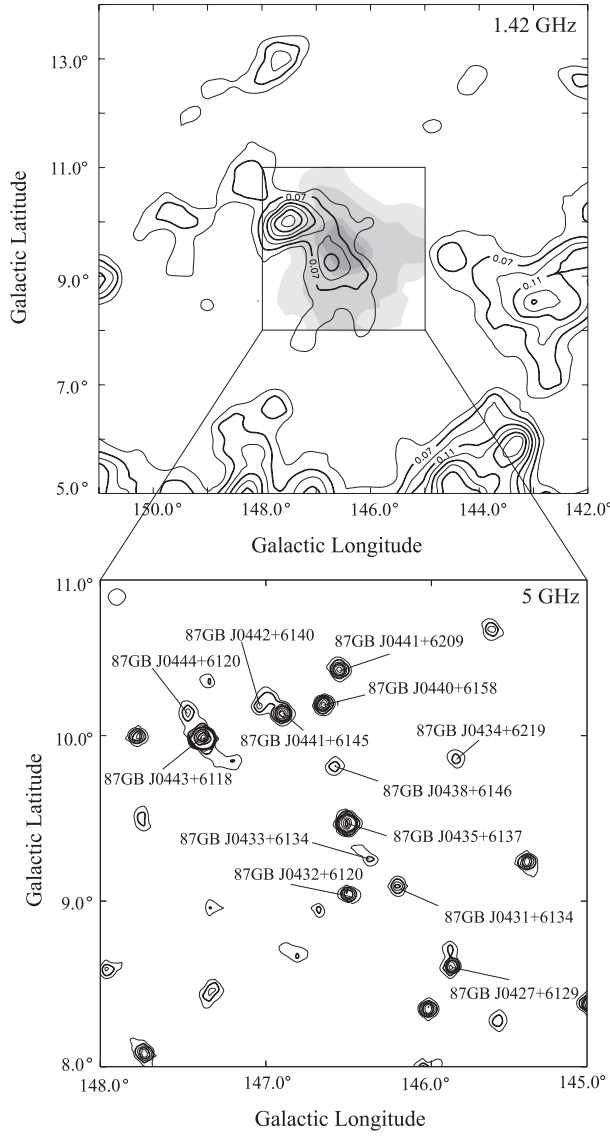
**Fig. 2.** Variability index distribution. The spline curve is the best Gaussian fit, it peaks at  $I = 2.0$  and presents a standard deviation of  $\sigma_I = 0.7$ . These values suggest that most of the unidentified sources are variables.



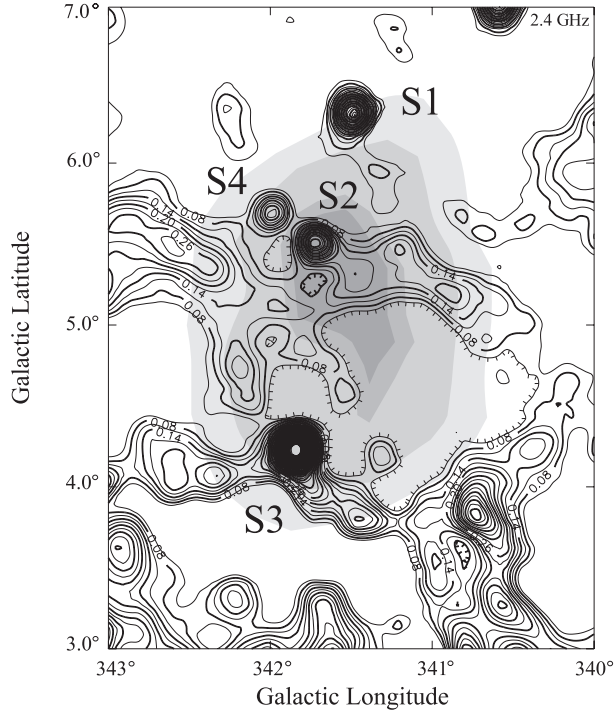
**Fig. 3.** Variability index distribution for the 66 AGNs in the 3EG catalog. The spline curve is the best Gaussian fit, it peaks at  $I = 2.3$  and has a standard deviation of  $\sigma_I = 0.8$ .



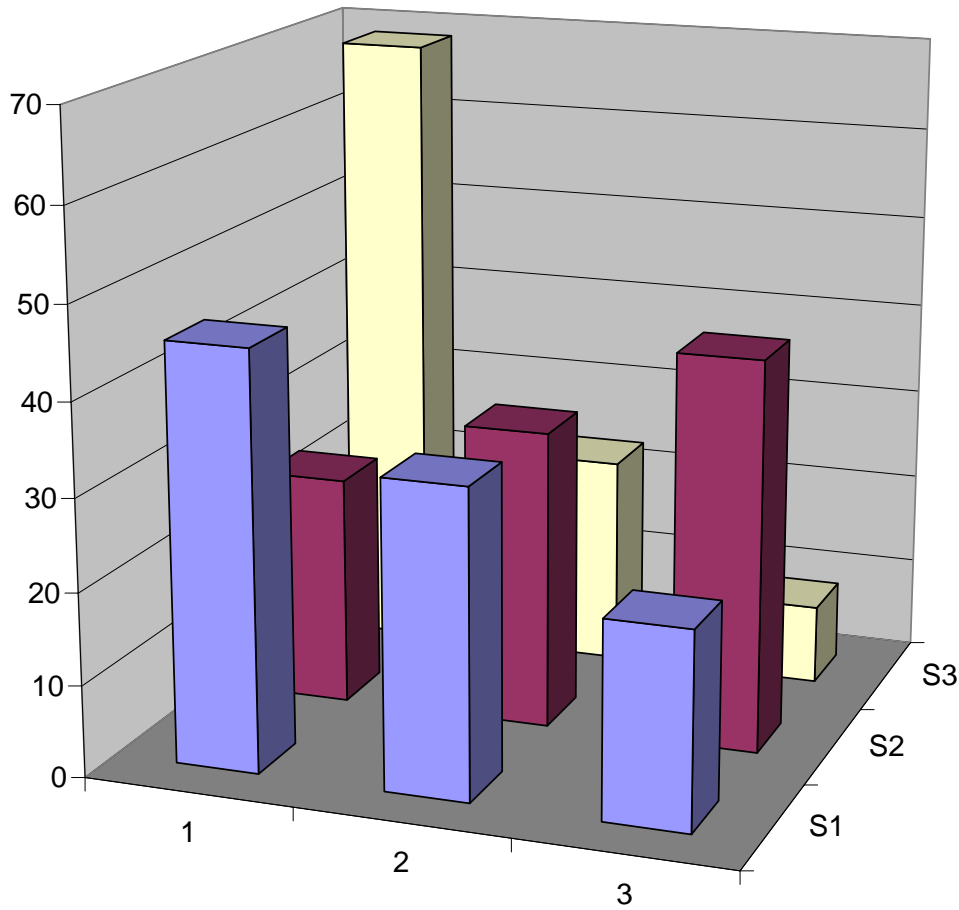
**Fig. 4.** Variability versus photon spectral index plot. We also present the values for 7 pulsars and 66 AGNs in the 3EG catalog. Horizontal solid lines represent the lowest and maximum values for pulsars. The dotted line corresponds to the limit above which all sources are variable with high confidence ( $3\sigma$ ).



**Fig. 5. Upper panel:** Map of the radio field around 3EG J0435+6137 at 1.42 GHz (angular resolution of  $34'$ ) with the diffuse emission filtered using a beamwidth of  $120' \times 120'$ . Contours are labeled in steps of 0.02 K from 0.05 to 0.22 K in brightness temperature. The superimposed grey-scaled levels represent the 99%, 95%, 68%, and 50% statistical probability that the gamma-ray source lies within each contour. **Lower panel:** Image at 5 GHz of the central field obtained with the former NRAO 91-m telescope at Green Bank (Condon et al. 1994). Contours are shown starting at  $10 \text{ mJy beam}^{-1}$ , in steps of  $10 \text{ mJy beam}^{-1}$ .



**Fig. 6.** Radio image of the field of 3EG J1631-40 at 2.4 GHz (angular resolution of 10.4') after the subtraction of the diffuse emission. Superimposed to the radio image we show the confidence contours of the likelihood test statistics of the EGRET detection. The best result for revealing a counterpart of the gamma-ray source is obtained for a filtering beamwidth of  $90' \times 90'$  and 6 iterations. Radio contours are shown at steps of 0.05 from 0.05 to  $6 \text{ Jy beam}^{-1}$ .



**Fig. 7.** Unidentified sources variability. The three columns labeled with S1 represent the percentage distribution of the variability index  $I$  of the whole sample of 75 unidentified low latitude sources. From left to right, the numbers 1,2,3 stand for non-variable (45.3%), variable (33.3%) and highly variable sources (21.3%). S2 represent the group of 40 sources studied in this paper, without positional correlation. The percentage distribution is 1: 25%, 2: 42.5%, and 3: 32.5%. Finally, S3 represent the group of 35 sources which presented positional correlation with known objects, and its distribution is 1: 68.5%, 2: 23%, and 3: 8.5%.